d States
rtment of
ılture

ıltural
ırch
ce

February 1988

ARS Strategic Groundwater Plan

1. Pesticides

Foreword

The Agricultural Research Service has a longstanding and deep commitment to protecting our Nation's groundwater resources. A large portion of our rural population relies on groundwater as the primary source of their drinking water. Our livestock, farming, and ranching operations in many areas rely totally or in part on groundwater. They also depend on agricultural chemicals to protect and nurture their crops and animals. This research plan recognizes the important role chemicals play in modern agriculture and provides a balanced approach that allows continued use of these valuable production aids in a manner that minimizes their movement into groundwater. It focuses on the major commodities, primarily corn, soybeans, small grains, and cotton. Finally the plan recognizes the need for cost-effective solutions that will sustain a competitive agriculture well into the next century. The recommendations contained in this plan deserve the serious consideration of producers, agribusiness, State and Federal agencies, concerned citizens, scientists, and engineers.

T.J. Army
Deputy Administrator, NPS

Overview

The use of pesticides to sustain agriculture in the United States has increased enormously since the end of World War II. Now, roughly 330 thousand tons of pesticides are applied yearly on U.S. crops. With this widespread use arises the potential for some pesticides to move downward from application sites and into the Nation's groundwater. To help safeguard that water supply, upon which millions of people depend, ARS has developed the ARS Strategic Groundwater Plan for pesticides (part 1) and nitrate (part 2), another potential contaminant. The ultimate goal of the plan for pesticides is threefold: provide the American farmer with cost-effective best management practices (BMP's) to reduce pesticide movement into groundwater, identify the factors that accelerate or retard that movement, and provide computer models to predict those circumstances that lead to groundwater contamination. Toward this end, the pesticides plan identifies and elaborates on six areas of research that will be conducted according to criteria that include the need to minimize the potential for groundwater contamination by pesticides. The areas of research are—

1. Conservation tillage practices;
2. Computer models to help select best management farm practices;
3. Integrated pest management systems compatible with best management farm practices;
4. Improved pesticide application technology;
5. Water/pesticide management practices for irrigated or poorly drained cropland; and
6. New technologies for pesticide analysis and decontamination.

The first five areas of research will focus on the development of management systems to reduce groundwater contamination; the last area, on the development of emerging technologies for reducing the time and cost of pesticide analysis, reducing the amount of field testing, controlling the dissipation of pesticides in the environment, and solving the difficult problem of managing wastewater from pesticide mixing and cleanup operations.

Research in these areas will be based on two assumptions: (1) a small fraction of some pesticides applied in agriculture does reach groundwater, although the magnitude and scope of the contamination are uncertain, and (2) improper wastewater disposal practices (point source) may be a significant factor contributing to the presence of pesticides in groundwater.

ARS is committed to conducting groundwater research, as set forth in the "Agricultural Research Service Program Plan: 6-Year Implementation Plan, 1986-1992."[1] In fact, among the high priority needs identified by the 6-year plan for soil and water conservation research, the first mentioned is "improved technology for preventing or reducing groundwater contamination by agricultural chemicals."

At present, ARS has basic research programs on pesticide leaching, sorption, metabolism by micro-organisms, uptake by plants, volatilization, and analytical detection in soil and water. ARS also has a major research effort on modeling those management, environmental, and soil factors that determine leachability of pesticides into groundwater. Segments of this research are being conducted in 12 laboratories at 9 locations in the United States: Beltsville, MD (4); Tifton, GA; Stoneville, MS; Baton Rouge, LA; Phoenix, AZ; Riverside, CA; University Park, PA: El Reno, OK; and St. Paul, MN.

Because the groundwater plan emphasizes solution-oriented research, some ongoing environmental research on pesticide mobility, fate, effects, and processes will be augmented by additional emphasis on chemical management under diverse field conditions. This action may require a substantial shift in program direction.

The plan encourages collaboration with other Federal and non-Federal research organizations, particularly the Soil Conservation Service (SCS), Extension Service (ES), Cooperative State Research Service (CSRS), Environmental Protection Agency (EPA), Geological Survey (GS), universities, and State experiment stations.

It may call for altering current agricultural management systems and modifying some SCS technical guides—activities for which ARS has unique expertise. Research called for in the plan will not duplicate any nationwide groundwater-monitoring programs, which are better carried out by EPA and GS.

[1] Agricultural Research Service Program Plan: 6-Year Implementation Plan, 1986-1992. U.S. Department of Agriculture, Agricultural Research Service. 1985.

1. Conservation Tillage Practices

Background
Between 60 and 70 percent of all U.S. cropland will likely be farmed according to some type of conservation tillage by the year 2000. The Food Security Act of 1985 contains several conservation provisions, one of which requires that farmers with highly erodible land reduce soil erosion to acceptable limits by 1990. For much of this land, conservation tillage may be the only economical way to limit soil erosion.

Conservation tillage has already proved to be a practical way to minimize nonpoint-source contamination of surface water because it reduces runoff and erosion. But it also increases infiltration and the potential for pesticides to leach below the root zone. Whether it also increases the concentration of pesticide residues in groundwater, however, has yet to be determined.

Current Effort
The effect of conservation tillage on the fate of pesticides is currently under study at 10 ARS locations (Colorado, Georgia, Illinois, Indiana, Maryland, Minnesota, Mississippi, North Dakota, Oklahoma, and Washington) (fig. 1). These locations represent several major physiographic regions, including the potentially vulnerable Atlantic Coastal Plain. Comparisons are being made between conventional (moldboard plow) tillage, no-till, mulch tillage, ridge tillage, and chisel plow tillage. Corn, soybeans, wheat, and sorghum are used in the cropping systems; and the pesticides include many major herbicides.

Plans
The effects of conservation tillage and conventional tillage on groundwater quality will be evaluated as each of the activities listed below is conducted:

1.1 Inventory current findings within ARS and, to the extent possible, those of other sources; then, critically examine them to establish whether conservation tillage does affect pesticide leaching and whether general tillage/pest-management recommendations can be developed for the major geographic regions of the United States.

1.2 Expand research efforts, as necessary to obtain data for other sites, climates, soils, hydrologic regimes, and agronomic management situations.

1.3 Focus ARS research on three crops (corn, soy beans, cotton) and four pesticides (atrazine, alachlor, metribuzin, carbofuran). Include a detailed soil survey in conducting all field studies.

1.4 Formulate best management practices to control macropore flow (preferential flow) to minimize pesticide leaching on the basis of tests that include such practices as crop rotation and subtillage.

1.5 Establish crop residue and pesticide placement combinations to optimize crop production and minimize leaching risk in vulnerable soils.

1.6 Determine which pesticide formulations minimize leaching.

1.7 Evaluate the combined impact of tillage and terracing on groundwater quality.

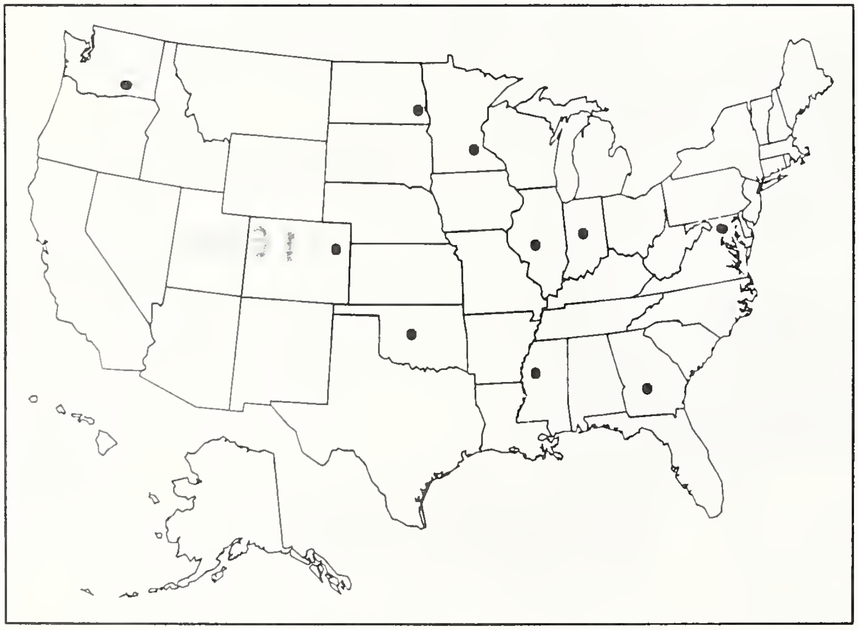

Figure 1.
ARS conservation tillage research sites representing several major physiographic regions. The sites are in Washington, North Dakota, Minnesota, Colorado, Illinois, Indiana, Maryland, Oklahoma, Mississippi, and Georgia.

2. Computer Models To Help Select Best Management Practices

Background

Ideally, models to help farmers select best management practices that minimize pesticide movement into groundwater would be developed upon a broad base of data on soils, climates, pesticide properties, crops, and management considerations. Because of limited time and resources, however, experimental data can be obtained for only limited combinations of these variables. Models must therefore be able to provide farmers with a selection of best management practices by extrapolating from the available database. For example, models may have to provide a selection to be used with a new pesticide or formulation; that is, one for which no field data exist. Or they may have to provide a selection that would account for the frequency with which certain climatic events occur in a long-term weather cycle. Models integrate data from many sources to provide useful information to farmers and are thus an important tool for technology transfer.

ARS has an excellent record of developing and delivering models for research and for action-agency application. Some of these are USLE (Universal Soil Loss Equation), EPIC (Erosion Productivity Impact Calculation), CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems), and GLEAMS (Groundwater Loading Effects of Agricultural Management Systems). Other models that also predict the effects of agriculture on groundwater quality are under development and testing by ARS, by other agencies such as EPA and GS, and by some universities. Several of these models depend heavily on USDA technology. Despite these efforts and because transport in the environment is becoming increasingly important as a reason for restricting pesticide use, additional effort is needed in the area of models research.

Current Efforts

Research on modeling can be divided into three subareas: models—their construction, validation, and testing for operational effectiveness; databases—development for model input and validation; and information delivery (technology transfer) systems. Research is underway in all three subareas at various locations. Conceptually, ARS research on models consists of (1) testing the applicability of existing operational models (for example, GLEAMS), (2) developing new user models (for example, the Root-Zone Water-Quality Model, RZWQM), and (3) developing research models based on comprehensive information on pesticide processes in the soil (for example, volatilization, degradation, adsorption) and on spatial and temporal variability. Several locations are contributing toward development of the databases, and ARS' Model and Database Coordination Laboratory is coordinating activities on delivery systems.

Plans

Essentially all the current programs will be continued in the near future, as reported in the respective CRIS documents. Future work will be the following:

2.1 Determine best management practices for minimizing pesticide leaching to groundwater as a function of soil, climate, and other environmental conditions (Beltsville, MD; Urbana, IL; El Reno, OK; St. Paul, MN; Tifton, GA).

2.2 Extend existing models to more fully account for those factors that increase or decrease pesticide mobility and persistence (Beltsville, MD; Baton Rouge, LA; W. Lafayette, IN; Riverside, CA).

2.3 Document, test, and evaluate the limitations of current field-scale models most likely to have the greatest impact on groundwater integrity (Beltsville, MD; Ft. Collins, CO; Riverside, CA; Tifton, GA; Phoenix, AZ; Stoneville, MS).

2.4 Gain knowledge about basic pesticide processes so that it can be used to improve model simulation of the fate of pesticides in agricultural environments (River side, CA; Beltsville, MD).

2.5 Expand the physiochemical databases of pesticides to develop management systems that will reduce the potential for groundwater contamination (Beltsville, MD; Tifton, GA).

2.6 Improve existing models to assist in selection, evaluation, and implementation of new technologies and practices (such as slow-release formulations, pesticide scheduling, and selective placement) for limiting pesticide leaching.

Expectations are that—

- Application testing of the GLEAMS model inhouse and by selected users will be complete within 2 years;
- The RZWQM model will be operational and available for use within 1-3 years;
- Methodologies for selection of BMP's will be tested with available data during the next 5 years;
- Expanded databases on selected pesticides will be available within 1 year;
- Conceptual links between pesticide/root-zone models and crop-management/pesticide-application technol ogy will be developed within 3 years; and
- New mathematical formulations of processes will be incorporated into operational models from time to time over the next 5-10 years.

3. Integrated Pest Management Systems Compatible With Best Management Farm Practices

Background

Mechanical, cultural, biological, hand-labor, and chemical methods can be used in various combinations to develop integrated weed management (IWM) systems for preventing serious losses in crop production. Similarly, combinations of cultural, biological, genetic, and chemical methods can be and often are used in integrated pest management (IMP) systems for combating nematodes, harmful arthropods, insects, and disease causing organisms—pests that are less universal problems than weeds but capable of even greater destruction. Pesticides are extremely important in IWM and IMP systems because they control pests either more effectively or more economically than other methods. But some pesticides persist in soil, and some leach deeply enough to become potential contaminators of groundwater. Therefore, effective pest control systems that have minimal potential to allow such persistence and leaching and that, moreover, are compatible with best management practices must be developed.

Current Effort

Numerous scientists are conducting research to develop pest control systems that are economical; effective against pests; and safe for crop plants, consumers, wildlife, and succeeding crops.

Plans

The current effort will continue but with two requirements. The first is that the control systems minimize the movement of pesticides below the first 3 feet of soil—a depth well below the usual zone of pest control. The other requirement is that the control systems be cost effective, practical, and compatible with best management practices. Researchers will be doing the following:

3.1 Use pesticides formulated in controlled-release carriers.

3.2 Substitute low persistence, nonleaching pesticides for persistent, leachable pesticides whenever feasible.

3.3 Determine periods when pest control is needed, and apply only the quantities of pesticide needed during these periods.

3.4 Apply pesticides only within the rows (band application), and control pests by nonchemical methods between the rows.

3.5 Use mechanical methods, foliar-active pesticides with low soil persistence, or biological control methods rather than persistent soil-active pesticides.

3.6 Rotate crops requiring persistent, leachable pesticides with crops requiring nonpersistent pesticides.

4. Improved Pesticide Application Technology

Background

Over 90 percent of all pesticides are applied as sprays on either foliage or soil. When pesticides are sprayed on soil, the dosages are often raised to compensate for losses due to volatilization, photodecomposition, leaching, microbial degradation, and adverse environmental factors. Increasing the dosages, however, increases the potential for the pesticides to leach into the soil and, perhaps, even below the first 3 feet. For herbicides to be most effective, they should remain in the top 1 inch of soil, where most weeds originate. Application technology that would minimize both the untimely loss of pesticides and the potential for pesticides to leach below the first 3 feet of soil must be developed.

Current Effort

Two promising pesticide application techniques under intensive study are chemigation—the application of chemicals with irrigation water supplied specifically by a sprinkler or drip system—and controlled release of pesticides.

Chemigation has been shown to be an effective way to apply certain pesticides, but its effect on pesticide leaching has yet to be fully examined. Studies on controlled-release methods focus mainly on the development of pesticide formulations. With further work, both techniques should come to be as widely used as conventional methods of applying chemicals; that is, use of sprays and such pesticide formulations as wettable powders and emulsifiable concentrates. Results from tests conducted thus far with several pesticides indicate that starch encapsulation will feature importantly in the further development of controlled-release formulations. For example, one such study showed that aphids responsible for the spread of barley yellow dwarf virus were controlled more effectively and selectively by starch-encapsulated carbofuran, a systemic insecticide, than by conventional formulations of the insecticide. Starch coatings provide not only for the controlled release of pesticides but also for their protection from rapid volatilization, degradation by light and micro-organisms, and leaching.

Plans

The major objectives are to conduct work in three subareas:

4.1 Conventional application technology—Determine how split applications, banding, synergistic additives, time of application, pesticide combinations, and postemergence applications affect the potential for groundwater contamination. Determine the cost-effectiveness of these alternative application methods and their potential for reducing overall pesticide application rates.

4.2 Chemigation—Determine whether chemigation in creases or decreases groundwater contamination; and if it increases, what techniques could be developed to reduce this problem.

4.3 Controlled-release formulations—Determine and quantify the effect of formulation on the following pesticide characteristics and processes: sorption by soil, volatility, loss by runoff, leaching, persistence, selectivity, and efficacy. Determine cost/benefit relationships for different pesticide formulations and the extent to which pesticide application rates can be reduced. Determine the extent to which these application technologies can effectively address the needs and problems of alternative/sustainable agricultural systems. Determine the feasibility of developing controlled-release formulations of metham-sodium (Vapam) to control its volatility and leachability without reducing its effectiveness as a multifunctional soil-applied pesticide for controlling weeds, insects, plant pathogens, and nematodes.

5. Water/Pesticide Management Practices for Irrigated or Poorly Drained Cropland

Background

Pesticide movement through the root zone is closely related to water movement. Consequently, changing water management practices can greatly affect pesticide movement. In humid areas, irrigation often supplements rainfall, but in semiarid areas, irrigation is the main source of water for crops. Many pesticides are being applied in water supplied by flood irrigation. There is concern, however, that this practice as well as that of irrigating soon after pesticide application will accelerate movement of the pesticides to groundwater. Nonuniformity of water application and low irrigation efficiencies will exacerbate this problem. Newer irrigation techniques have been developed to increase irrigation efficiency while maintaining high yield. We need to examine how these new techniques can be used to minimize leaching of pesticides below the root zone. There is also concern that pesticides in shallow groundwaters will reach the deeper aquifers used for farm and (in many cases) urban water supplies. Shallow groundwater drainage systems can be used as a management tool to limit the risk of contaminating deeper aquifers with pesticides.

Current Effort

Transport of pesticides under flood irrigation and the role of preferential movement in soils are being studied (Phoenix, AZ). Field plot experiments are underway on how best to apply herbicides and irrigate without allowing their deep leaching. Comparisons are being made on the effects of flood irrigation vs. sprinkler irrigation on the leaching of herbicides sprayed onto the soil surface. Also, for field plots receiving flood irrigation, comparisons are being made on the leaching of herbicides applied by spray onto the soil surface vs. the herbicides applied with the irrigation water.

Plans

5.1 Evaluate the economic and environmental consequences of modifying irrigation practices and the application time(s) and placement of pesticides to reduce pesticide movement to groundwater. Specifically, compare pesticide movement under new methods of surface irrigation with that under sprinkler and drip irrigation, using various application times and placements of the pesticides and also using two locations with different soil types. Evaluate the effect of chemical and physical properties of the pesticides on their relative movement (Riverside, CA; Phoenix, AZ).

5.2 Determine the leaching potential of various pesticides when weather forecasts and groundwater drainage systems are used to control water table levels. Determine what conditions and inputs are needed to reduce the downward leaching of pesticides applied singly or in various combinations with other components (Baton Rouge, LA; possibly Columbus, OH).

6. New Technologies for Pesticide Analysis and Decontamination

The recognition that groundwater is vulnerable to contamination by pesticides has prompted researchers to act quickly to protect our groundwater. They have begun work to develop technologies for testing the efficacy of management practices to minimize pesticide leaching; for detecting pesticide residues rapidly, accurately, and economically; for predicting the environmental fate of pesticides; for decontaminating wastewaters, soils, and aquifers; and for altering pesticide persistence in soil. These developmental efforts will be continued and are discussed in greater detail under separate headings.

6A. Evaluation of Pesticide Management Practices by Laboratory/Greenhouse Screening Tests

Background

Pesticide management practices that significantly reduce pesticide leaching are difficult and expensive to evaluate under field conditions. Year-to-year variabilities in climatic and soil factors can have a greater effect on leaching than the management practices themselves. Thus, we need to develop simple laboratory/greenhouse tests that will rapidly and accurately identify the most promising management practices for reducing groundwater pollution. The tests could be made with soil cores obtained from field plots. Once these management practices have been identified, they can be field tested.

Plans

6A.1 Develop techniques to obtain intact soil cores (6-inch minimum diameter by 12-inch depth), that is, without disrupting the natural soil structure.

6A.2 Develop equipment for applying pesticides uniformly to the core surface.

6A.3 Develop techniques for extracting and analyzing pesticides in core leachate, soil solution, and soil after leaching.

6A.4 Develop standardized methods for quantitating differences among pesticides in leachability, and differences among soil variables and among management practices in their effects on pesticide leachability.

6B. Sensitive, Rapid Methods for Pesticide Detection

Background

The recognition that groundwater may contain trace quantities of agricultural chemicals has aroused public concern and created a demand for extensive programs of groundwater surveillance and monitoring. Techniques in current use for measuring trace residues of pesticides in soils and groundwater are complex, labor intensive, and costly, requiring sophisticated instrumentation. Nevertheless, they are also sensitive and specific, so they will continue to be useful. They could, however, be improved by automation or use of robotics, particularly for extraction and cleanup of extracts.

An innovative approach to detecting traces of pesticides or other organics is to use biosensors. Biosensors have thus far been developed primarily for clinical applications, but their use in industry may soon expand greatly because they can be used for early detection and, therefore, for many process-control applications. They would be a powerful tool for measuring contaminant levels in a flowing liquid.

Biosensors consist of an electronic device attached to a substrate-specific bioactive substance. When the bioactive substance reacts with the substrate—a pesticide, for example—the electronic device produces a signal, which can then be detected. Enzyme electrodes are one type of biosensor and consist of an electrochemical sensor coated with a layer of enzyme. The analyte is often the substrate or product of the enzymic reaction. The bioactive substance may also be whole microbial cells, and this type of biosensor offers opportunities for detecting many microbial reactions. In yet another type of biosensor, the bioactive substance participates in an immunological reaction. Immunoassays for several pesticides are commercially available and are being evaluated for applicability in groundwater analysis by ARS and other agencies. An important consideration in designing new biosensors is sensitivity. This can be improved by amplification of the signal from the electronic device.

Plans

6B.1 Examine and evaluate novel and automated approaches to sample extraction, cleanup of extracts, and detection of analytes to reduce time and cost of analysis without loss of sensitivity and specificity.

6B.2 Develop and evaluate biosensors that can highly sensitively and specifically detect pesticides in groundwater and measure their levels.

6B.3 Evaluate available commercial systems such as immunoassay kits to determine whether they can be used to screen large numbers of water samples for the presence of pesticides.

6C. Input Data for Computer Models That Predict the Environmental Fate of Pesticides

Background

Pesticides may be dissipated in the environment through dispersion (leaching or volatilization, for example) and degradation through microbial, chemical, or light-induced reactions. The environmental fate of a soil-applied chemical depends largely upon its physical and chemical properties and its interactions with soil and climate. Thus, how accurately we can predict pesticide fate and how effectively we can prevent pesticides from leaching into groundwater depend largely on how well we understand these dissipation processes.

For modeling pesticide processes in soil and groundwater, three types of data are important: climate, soil, and chemistry of the pesticide. Soil and climatic data vary with the site, whereas chemical data vary with the pesticide. Some chemical data are obtained readily and accurately by standardized procedures, but others are difficult to obtain and more readily estimated because of elaborate techniques or precise control of physical parameters needed for their measurement. The literature provides evidence of the wide variability to be expected for data that are difficult to obtain.

Of particular importance in modeling efforts are partition coefficients that describe the distribution of pesticides among air, water, and soil. They relate to the transport of pesticides in the atmosphere and through the soil, including lateral movement within aquifers. For this reason, partition coefficients are vital input data for predictive models. Some concerns exist with present methods for determining pesticide partition coefficients. The unknown effects of soluble organic matter on the measured coefficients between air and water (Henry's Law constant) is one such concern because environmental samples commonly contain dissolved organics. The distribution of pesticides between soil and water is often determined by shaking a soil sample with a dilute aqueous solution of pesticide until equilibrium (in pesticide concentration) is reached. The fraction of pesticide that partitions into soil is adsorbed on the soil surface. Partition coefficients determined by this batch adsorption method do not always correlate well with results obtained from undisturbed field soils, perhaps because of marked differences in accessibility among adsorption sites in undisturbed soil. Typically, adsorption is well correlated with soil organic matter content. As organic matter content and other parameters vary spatially across a field, adsorption and leaching are also expected to vary. We need to improve our ability to translate laboratory-derived adsorption data to account for known variability in the field.

Plans

6C.1 Determine the effect of dissolved organic matter on pesticide partitioning between air and water, using the wetted-wall or other method.

6C.2 Reevaluate the conventional batch method for determining pesticide partitioning between soil and water. Also, investigate whether other published procedures will give partition coefficients that better correlate with observed field behavior of pesticides.

6C.3 Determine the field variability of measured pesticide adsorption, and input these data into pesticide transport models.

6D. Decontamination and Pesticide Persistence

Background

As awareness that pesticides can contaminate soils and aquifers increases, the need for methods to remove or reduce such contaminates also increases. High concentrations of pesticides in wastewater from point sources, such as spray-tank mixing areas, are major concerns in our efforts to prevent groundwater contamination. Some highly productive soils are vulnerable to excessive movement of pesticides because of their low organic matter and clay contents or high water tables. Once a subsurface soil or aquifer becomes contaminated, the contaminant dissipates at an extremely slow rate. Present technologies cannot readily hasten the dissipation. However, novel technologies are emerging which have the potential to decontaminate pesticide-containing wastewaters, to accelerate the natural decontamination processes in soils and aquifers, and to prevent pesticide movement in highly vulnerable soils.

Plans

6D.1 Develop microbial systems that will decontaminate wastewaters, soils, and aquifers. Bioreactors may be used successfully to treat wastewaters, but in situ systems are needed for soils and aquifers. Isolate and manipulate genes in soil micro-organisms to improve their ability to degrade pesticides and thus decrease their persistence specifically in subsoil and aquifer environments.

6D.2 Explore the use of chemical additives and micro-organisms to modify soil organic matter and tilth, and thereby modify the capacity of soils to sorb pesticides.

United States
Department of
Agriculture

Agricultural
Research
Service

March 1988

ARS Strategic Groundwater Plan

2. Nitrate

Foreword

The Agricultural Research Service has a longstanding and deep commitment to protecting our Nation's groundwater resources. A large portion of our rural population relies on groundwater as the primary source of its drinking water. Our livestock, farming, and ranching operations in many areas rely totally or in part on groundwater. They also depend on agricultural chemicals to protect and nurture their crops and animals.

This research plan recognizes the important role that nitrogen fertilizers play in modern agriculture and provides a balanced approach that allows their continued use in crop production in a manner that minimizes the movement of nitrogen into groundwater. It focuses on the major commodities, primarily corn, soybeans, small grains, and cotton. Finally, the plan recognizes the need for cost-effective solutions that will sustain a competitive agriculture well into the next century. The recommendations contained in this plan deserve the serious consideration of producers, agribusiness, State and Federal agencies, concerned citizens, scientists, and engineers.

T.J. Army
Deputy Administrator, NPS

Overview

Supplying this Nation's crops with adequate nitrogen (N) is vital to ensuring the safety and security of our food supply. The aim of U.S. agriculture is to provide crops with N in amounts needed for economically optimum yields. Providing crops with too little N results in decreased yields and poor economic returns, while providing them with too much may result in the accumulation of mineral forms of N (ammonium and nitrate) within the crop root zone. These high nitrate accumulations may eventually leach out and contaminate groundwater and surface water supplies.

Estimates are that for the 1985/86 and 1986/87 crop years, U.S. cropland annually received 10.6 million tons of N through commercial fertilizers (Follett et al. 1987) plus another 9.2 to 10.8 million tons through the return of manures, crop residues, rainfall, and biological fixation (R.D. Hauck, Agriculture Research Branch, Tennessee Valley Authority, personal communication 1988). Once N from these various sources is added to the soil, it is subject to transformations that take place in the nitrogen cycle (figure 1), including transformation to nitrate. Nitrate is soluble and moves with the soil water. When precipitation or irrigation amounts exceed crop water use, the soil water and its dissolved nitrate percolate down through the crop root zone and eventually become part of groundwater. Other sources that may contribute major quantities of nitrate to groundwater are geologic deposits (Viets and Hageman 1971), forests and pastures, and urban wastes (Keeney 1986).

Concern arises when too much nitrate accumulates in groundwater, because when ingested in high enough amounts by humans and animals, nitrate has potential adverse health effects, such as methemoglobinemia and cancer (CAST 1985, Keeney 1986). Under some conditions nitrate can form nitrosamines, which have been suggested as possible carcinogens in humans (Keeney 1986). On the basis of the methemoglobinemia information, the Environmental Protection Agency (1976, 1982) has set the maximum allowable concentration of nitrate in public water supplies at 45 parts per million (ppm), or 10 ppm N in the nitrate form.

In a recent survey of water analysis data for nearly 124,000 wells across the United States, Madison and Brunett (1985) separated the data according to ranges of nitrate-N concentrations. Recognizing that the wells tested do not necessarily represent a random or unbiased sampling of all wells or aquifers in the United States, the data showed that 80.4 percent of the wells had a nitrate-N concentration below 3.0 ppm; 13.2 percent, a concentration between 3.0 to 10 ppm; and 6.4 percent, a concentration exceeding 10 ppm. Groundwater, which is the source of well water, provides drinking water for about half the U.S. population and for about 85 percent of the rural population (CAST 1985). Its quality must therefore be safeguarded.

This publication presents the ARS Strategic Groundwater Plan for nitrate. Its purpose is to identify areas of research that will result in technologies to minimize leaching of nitrate from agricultural land to groundwater, while maintaining or enhancing N-use efficiency and the competitiveness of U.S. agriculture. The following six high priority areas of research have been identified:

1. Improving estimates of mineral N requirements for optimum crop production;
2. Effects of N transformations on crop N requirements and N leaching;
3. Management of fertilizer N and soil amendments;
4. Minimizing the impact of nitrate leached from the crop root zone;
5. Computer models to help select best management farm practices; and
6. Emerging technologies.

The first five areas of research will focus on the development of management practices to reduce groundwater contamination; the last area, on the development of emerging technologies for controlling the leaching of nitrate into groundwater as well as into surface water. Research in these areas will take into account changing farm practices, such as the shift toward conservation tillage. Projections are that conservation tillage will be used on 60 to 70 percent of all U.S. cropland by the year 2000, so its importance must be recognized in the overall program on nitrate management.

Research in these areas will be based on three premises: (1) indigenous soil N, added and recycled N, and N from geological sources can all contribute toward the leaching of nitrate into groundwater, so these N sources must be accounted for in a total N management system; (2) N transformations and N-transport processes must be considered in the development of best management practices; and (3) managing and controlling nitrate concentrations at shallow soil depths are essential for minimizing the leaching of nitrate from the crop root zone.

ARS is committed to conducting groundwater research, as set forth in the "Agricultural Research Service Program Plan: 6-Year Implementation Plan, 1986-1992" (U.S. Department of Agriculture, Agricultural Research Service 1985). In fact, among the high priority needs identified by the 6-year plan for soil and water conservation research, the first mentioned is "improved technology for preventing or reducing ground-water contamination by agricultural chemicals."

At present, ARS has research programs on the leaching, detection, plant uptake, and various biological transforma-

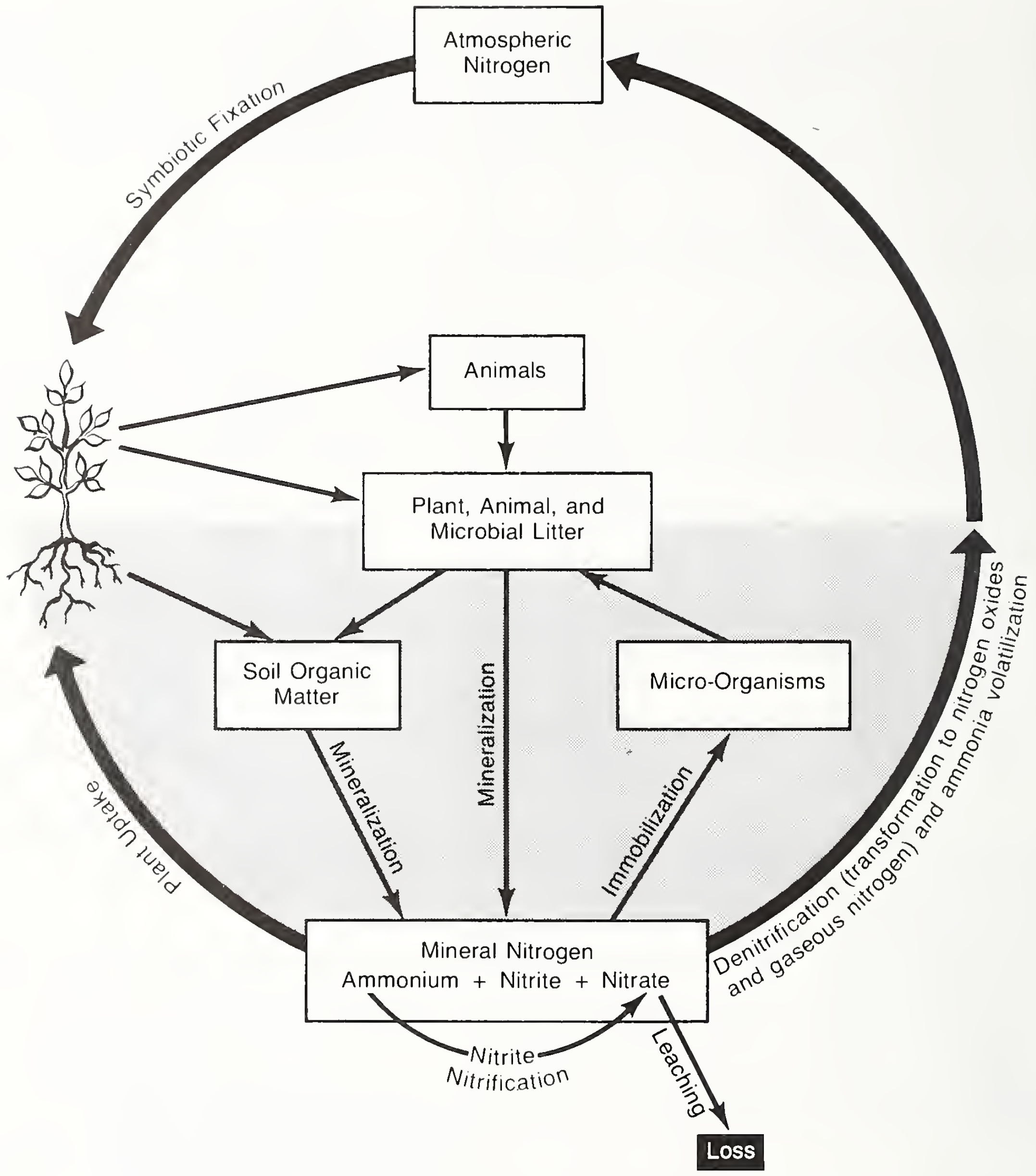

Figure 1.
The nitrogen cycle. (Adapted from Reeder and Sabey 1987.)

tions of N. Further, ARS has a major research effort on modeling those management, environmental, and soil factors that determine leaching of nitrate into groundwater. Segments of this research are being conducted in laboratories at 14 locations in the United States: Riverside, CA; Akron and Fort Collins, CO; Tifton, GA; Ames, IA; Kimberly, ID; Beltsville, MD; St. Paul, MN; Lincoln, NE; Mandan, ND; Columbus and Coshocton, OH; Durant, OK; and University Park, PA. Intentions are to expand research efforts, as necessary, to obtain data for other sites, climates, soils, hydrologic regimes, and agronomic management situations.

Because the groundwater plan emphasizes problem-solving research, some ongoing work on nitrogen processes and nutrient cycling will be augmented to include evaluations of the effects of N management under diverse field conditions. It is anticipated that a substantial shift in program direction will be required.

The plan provides a framework for coordination and collaboration with other Federal and non-Federal organizations, particularly the Soil Conservation Service (SCS), Extension Service (ES), Cooperative State Research Service (CSRS), Economic Research Service (ERS), Tennessee Valley Authority (TVA), Environmental Protection Agency (EPA), Geological Survey (GS), universities, and State experiment stations.

Research called for in the plan is consistent with the needs identified by SCS in its report entitled "1987 Soil and Water Conservation Research and Education Progress and Needs" (U.S. Department of Agriculture, Soil Conservation Service 1987). The work will not duplicate nationwide groundwater-monitoring programs, which are better carried out by EPA or GS. Rather, the plan is to develop improved soil management practices that protect groundwater while maintaining soil productivity and an economically viable agriculture.

1. Improving Estimates of Mineral N Requirements for Optimum Crop Production

Background

Most of the essential nutrient N is assimilated by crops in a mineral form, either as nitrate or ammonium. A growing crop can obtain and utilize mineral N from various sources—soil itself, soil organic matter, crop residues, legumes, manures and wastes, precipitation and irrigation water, and fertilizers. Preference for nitrate or ammonium depends on the crop species, variety or hybrid, and stage of growth as well as temperature, water regime, and other factors. Nitrate in the soil solution is susceptible to displacement into groundwater and/or surface water if precipitation causes it to leach before it is absorbed by plants. It should be recognized that management practices designed to restrict or impede surface movement of water in order to protect the quality of receiving surface water may increase the potential for nitrate movement into groundwater.

From research to date, we know much about the patterns of N uptake by plants. For example, we know that the demand for N in most crops is usually greatest within a few weeks before or after flowering. We also know that mild N stress during early vegetative growth often has little effect on the final yield of corn and certain other grain crops, but that excess mineral N supplied toward the end of the growing season may lower the quality and even yield of sugar beets, malting barley, and possibly other crops.

Despite our knowledge about N uptake patterns, we know little about the mineral N requirements of the various cultivars of different crops or about the concentrations of mineral N required in soil solution to satisfy the needs of crops during their various growth stages. We need this fundamental knowledge because we need to develop soil and crop management practices, particularly those including the use of conservation tillage, that will (1) provide crops with sufficient mineral N throughout the growing period to maintain satisfactory production, (2) minimize concentrations of nitrate in soil water during seasons when leaching is likely to occur, and (3) minimize the movement of nitrate out of the root zone toward groundwater. Yet another requirement for the development of these crop management practices is the ability to accurately predict the quantities of N that will be made available to the crops by transformation of N from organic sources (including microbial biomass) into mineral forms of N (mineralization). To gain this ability, we must better understand the operation of the nitrogen cycle and improve the accuracy and utility of various types of soil and plant tissue analyses.

Current Efforts

Much of the present work on the requirements for mineral N sufficiency is being conducted by ARS and State experiment station scientists. Experiment station scientists in a few States provide farmers with N fertilizer recommendations on the basis of soil tests. They measure either the residual nitrate or organic matter content of soils and estimate the potential mineralization rates as well as the credits for manures, legumes, and other pertinent factors. The N requirement of the crop is then considered, and the N fertilizer recommendation made. Adjustments for conservation tillage are rarely made. Although these recommendations usually lack a sound scientific basis and testing methods vary among the States, soil tests are still our best available tool for predicting crop fertilizer requirements. ARS scientists are developing improved methods for predicting N mineralization rates, analyzing plant tissues, determining the effects of species or variety/hybrid on N uptake rates and times, controlling N mineralization, and matching soils with crops according to N supply and need. The ARS facilities most heavily involved in this research are in Fort Collins, CO; Ames IA; Kimberly, ID; Beltsville, MD; and Lincoln, NE.

Plans

Work at the facilities referred to under Current Efforts will continue. Greater emphasis will be placed on the use of N isotopes because they allow us to gain more definitive information on the sources of N. The following work is planned:

1.1 Determine the N sufficiency levels of our major crops as a function of their growth stage, plant physiological requirements, and environmental conditions.

1.2 Assess the potential of soils to provide enough mineral N to meet the minimum N requirements of major crops, especially under conditions of conservation tillage. Focus on how rates of ammonium and nitrate formation in soil are affected by ambient conditions (particularly temperature and water regimes) and how these rates vary in relation to stage of plant growth (N requirement).

1.3 Evaluate alternative methods of measuring and predicting the quantity of potentially mineralizable N in soil and relate quantities mineralized to measurable soil properties. Methods developed through this research would have use in work plan 1.2.

1.4 Determine the mineral N form (nitrate or ammonium) or the ratio of mineral N forms preferred by crops at various stages of growth. There is evidence that some crops have a preference for a specific mineral form and that for corn and possibly other crops, this preference may vary according to the cultivar and growth stage.

1.5 Develop practices using nitrification inhibitors or other techniques to maintain soil N in a nonleachable form.

2. Effects of N Transformations on Crop N Requirements and N Leaching

Background

N added or returned to U.S. cropland through fertilizers, manures, crop residues, rainfall, and biological fixation averages about 127 to 137 lb/acre annually, based on the 1986 harvested area of 312 million acres (Agricultural Statistics 1987). By contrast, the top 6 inches of an acre of cropland contains 1,700 to 2,000 lb of N for each 1 percent of organic carbon (1.72% organic matter) contained in the soil. Soils frequently have an organic carbon content of 2 percent or more. Once placed on or in the soil, N from whatever source can undergo transformations in the nitrogen cycle. These transformations include immobilization (biological assimilation of mineral forms of N to form organic compounds), mineralization, nitrification (the microbial oxidation of relatively immobile ammonium to nitrite and then to nitrate), and denitrification (transformation of nitrate to nitrogen oxides and gaseous N). We have limited knowledge about the rates and timing of these various transformations and their effects both on crop N requirements at the various growth stages and on nitrate leaching. We need to gain this knowledge for conditions of both conventional tillage and conservation tillage. Because conservation tillage returns protective amounts of crop residue to the soil surface, it is more effective than conventional tillage in decreasing surface-water runoff and enhancing water infiltration. The residue also serves as an additional source of carbon and energy for microbes, which immobilize N in soil organic matter.

Current Efforts

Research to determine the effects of N transformations on crop N requirements and on leaching throughout the year is being conducted at six ARS locations representing several major physiographic regions (Fort Collins, CO; Kimberly, ID; Beltsville, MD; Lincoln, NE; Mandan, ND; and Durant, OK). Management systems include irrigated and rain-fed crops as well as conventional and conservation tillage. Corn, wheat, sorghum, forage legumes, and seed legumes are the test crops.

Plans

Essentially all of the current programs will continue, but researchers at several of the locations will be making greater use of isotopic N to identify both the sources of N and crop preferences for these sources. Future work will focus on the following:

2.1 Determine the extent to which crop N requirements can be satisfactorily met through mineralization of N from soil organic matter and/or crop residues, legumes, and manures without buildup of residual soil nitrate that can leach during periods of water percolation.

2.2 Determine the extent to which mineralized N from various sources undergoes nitrification and leaching during periods of maximum water percolation.

2.3 Through the use of conservation tillage with other management practices (for example, crop rotation, fertilizer management, crop residue placement), determine whether N transformations can be controlled to minimize soil nitrate accumulation and leaching.

3. Management of Fertilizer N and Soil Amendments

Background

About 10.6 million tons of fertilizer N is used annually in the United States, and this amount represents a major input of N into our crop production systems. By deciding on the type(s) of N fertilizer to use and on the rate, timing, and method of fertilizer application, producers can exercise considerable control over the accumulation of fertilizer-derived nitrate in the soil. But they cannot accurately predict or control the amounts of N that will be made available for crop use during the growing season from other major sources of N (soil organic N, crop residues, legumes and cover crops, manures, and wastes). So they often apply enough fertilizer to assure that an adequate supply of nutrients is always available for the crops. Under prevailing economic conditions, this practice provides cheap "insurance" against crop N deficiency and its associated economic loss. However, there is a risk that any unused fertilizer N will leach into groundwater.

To more accurately determine fertilizer N requirements, producers must have information on the mineralization rates of organic sources of N and the effect of different fertilizer management practices on the efficiency of fertilizer N use. Because of variabilities in soils, crops, and climates, fertilizer and soil management practices must be site specific. Producers also need information on the interactions of fertilizer management with crop residue and tillage managements, irrigation (including fertigation, which is the application of fertilizer with irrigation water), use of various amendments to control nitrate availability and uptake, and other related practices.

Current Efforts
Ten ARS facilities have substantial ongoing research on ways to improve the efficiency of fertilizer N use. Of these, five facilities have integrated their work with research on the microbiology of N transformations. They are using an integrated approach to examine the effects of conservation tillage and other practices on N availability, usage, and losses (including losses to groundwater). The 10 facilities are in Akron and Fort Collins, CO; Ames, IA; Kimberly, ID; Beltsville, MD; St. Paul, MN; Lincoln, NE; Mandan, ND; Coshocton, OH; and Durant, OK.

Plans

3.1 Determine soil and cropping conditions under which various regulators of soil and crop biology (for example, nitrification inhibitors, denitrification enhancers, urease inhibitors, slow-release fertilizers, plant growth hormones) might be used to control the soil nitrate levels during periods of high leaching potential.

3.2 For various combinations of soil, crop, and climate, evaluate the effects of tillage practices (especially conservation tillage) on the use efficiency of fertilizer N.

3.3 Examine how the interactions of tillage practices and other management practices (for example, fertilizer management, irrigation and fertigation, and cropping systems) affect the fate of fertilizer N. Use N isotopes to trace the fate of fertilizer N when feasible.

3.4 Develop fertilizer and management practices that synchronize soil nitrate availability with the N requirements of crops grown under conventional tillage and conservation tillage. To do this, examine fertilization rates, timing, and placement; fertilizer sources; and the soil, climatic, and cropping factors that control the synchronization.

3.5 Evaluate the potential for using cover crops (especially legumes, which can add to potentially mineralizable N pools) or double cropping strategies to control soil nitrate levels and water during noncrop seasons. Also, determine the efficiency of deep rooted crops to scavenge nitrate at depths normally below the root zone of major crops.

4. Minimizing the Impact of Nitrate Leached From the Crop Root Zone

Background
Nitrate that has leached below the root zone can sometimes be removed or diluted to provide both groundwater and surface water with acceptable quality. Removal is a viable option in watersheds that have (1) extensive, shallow water tables that are naturally or artificially controlled, (2) hydrologically active and heavily vegetated riparian zones, and (3) wetlands. Denitrification and, to a lesser extent, plant uptake are the principal removal mechanisms. Dilution is a major factor in determining water quality in mixed-land-use watersheds. Water quality can be enhanced by controlling both the acreage and hydrologic location of intensively farmed lands. Whether the method for minimizing the impact of nitrate leached below the root zone is removal or dilution, we need to establish the link between nitrate concentrations in the groundwater and nitrate losses from the field or source area. Unless we do so, we will be unable to develop site-specific best management practices (BMP's) and nitrate control strategies. Offsite or watershed management options that appear most promising for removing nitrate from shallow groundwater include controlling the depth of the water table for artificially drained soils and managing riparian zones and wetlands. An additional onsite, or farmland, option is to periodically plant deep rooted crops to mine nitrate from below the normal root zone depths.

Current Efforts
ARS has only limited research in this area. Much of the research is aimed at improving our understanding of the nitrate removal and dilution processes. Research includes water table management to promote denitrification and riparian zone management to enhance N uptake by deep rooted vegetation. The primary objective is to develop methods for evaluating the impacts of riparian zone management and farm management practices on groundwater quality for mixed-land-use watersheds. This research is being conducted at five ARS locations (Fort Collins, CO; Tifton, GA; Beltsville, MD; Columbus, OH; and University Park, PA).

Plans

4.1 Develop guidelines for estimating the efficiency of riparian zones in removing nitrate and the effect of this removal on the concentrations of nitrate in groundwater seepage and riparian zone aquifers. Develop the capability to estimate the effects of changes in riparian zone management.

4.2 Determine the impact of shallow, fluctuating water tables, both natural and induced (through use of artificial drainage-control systems), and that of temporary flooding in promoting denitrification. Formulate management practices that include denitrification.

4.3 Develop and incorporate into water quality models the capability to predict the effectiveness with which impoundments and wetlands remove nitrate from groundwater inflows.

4.4 Develop the capability to estimate the impacts of farm or field management options on the transport of nitrate to groundwater, particularly for diverse or mixed-land-use watersheds where dilution is a major factor. Use this capability to select the best watershed management options for minimizing nitrate entry into groundwater or associated streamflows.

4.5 Determine the efficiency of deep rooted crops to scavenge nitrate from depths lower than the normal root zone. Develop rotational or double cropping strategies that include the use of these crops if they are efficient scavengers.

5. Computer Models To Help Select Best Management Farm Practices

Background

Water movement and chemical fate in the root zone are controlled by management interactions with climatic and soil factors and are therefore site specific. Thus, for example, a nitrate management strategy developed for corn production may be environmentally defensible for prairie soils in Illinois but totally unacceptable for irrigated sands in Georgia. Because of limitations in time and resources, acceptable management practices cannot be developed for all the various crops, conditions, and locations in the United States. Instead, we need to develop simulation, or modeling, technologies that will evaluate present management practices and help us select BMP's and design new ones.

Simulation technology already exists within ARS in the form of field scale models for predicting the effect of agricultural management practices on the chemical loading of groundwater. We need to build upon these models and to establish supporting technologies for producing realistic simulations. Most of the new work will focus on the development of methods to estimate model input data that vary spatially. This work thus addresses probably the greatest single weakness of our simulation technology. Generally, however, conceptual depictions and model structure are adequate except in regard to soil macropore systems, which represent one aspect of spatial variability. ARS has already initiated some of this new work on methods. Once developed, they will have to be field tested and validated for key areas within the United States. For both the development and validation of these methods, researchers will have to obtain actual, representative field data. To do this requires the development of supporting sampling technologies.

Current Efforts

ARS has substantial model development programs at Fort Collins, CO, and Tifton, GA. Two approaches are being used in these programs. One is to develop simple N mass balance models (N input versus N removal) to flag excess applications of N and to suggest best remedial strategies to achieve N mass balance. The projected users of the models are people who make or use N fertilizer recommendations. The other approach being used is to develop models that test water, N, and crop management strategies for minimizing nitrate losses where overall N mass balance has essentially been achieved. Models developed through this approach are becoming available for testing and use at other ARS locations. The development of methods to estimate spatially variable data is ongoing but requires more coordination and focus. Only limited work is being done on macropores and the development of field sampling technologies.

Plans

ARS scientists in Riverside, CA; Fort Collins, CO; Tifton, GA; Beltsville, MD; St. Paul, MN; Lincoln, NE; Coshocton, OH; and University Park, PA, will be working to do the following:

5.1 Develop state-of-the-art, computer-based, user friendly models to achieve N mass balance and select BMP's for U.S. farmers, farm consultants, SCS, Extension agents, and others.

5.2 Develop or adapt nitrate leaching models to help select or develop BMP's. Incorporate these models into or tie them to crop production models, and focus on corn, soybean, wheat, and their common rotation crops first. Incorporate into these models the capability to handle irrigated and artificially drained lands.

5.3 Develop rapid, simple, and low cost techniques to estimate the spatially variable soil properties needed to model the nitrate concentrations and loads leached below the root zone. The primary data needed include hydraulic conductivity, bulk density, field capacity, maximum root zone depth, organic carbon content, potential N mineralizability, soil water content, and soil temperature.

5.4 Develop rapid techniques for estimating the macropore component, and adapt it for incorporation into the nitrate leaching models developed according to work plan 5.2.

6. Emerging Technologies

This section of the groundwater plan for nitrate presents examples of emerging technologies to control the leaching of nitrate below the root zone. The examples show that years of research are needed to provide the foundation for development of these technologies. In addition, ARS is preparing a publication on managing N for groundwater protection and farm profitability. It will be directed mainly to agricultural consultants, advisers, and producers.

Examples

- In temperate regions, the rates of N mineralization and nitrification are near maximum when 60 percent of the soil's pore volume is water filled, but the rate of denitrification begins to increase and dominate once the percentage of pore volume that is water filled increases beyond 80 percent. Simple techniques are being developed to determine how this information can be exploited in selecting optimum tillage and other management practices.
- Computer-based models incorporating improved scientific concepts are being readied for use in research and in action agencies to more closely simulate the leaching of nitrate from the crop root zone as a function of various combinations of soils, climates, and cropping systems.
- For farmlands with shallow water tables, cost-effective methods are being developed to raise (and lower) the water tables so that excess soil nitrate may be denitrified to gaseous N and released into the atmosphere.
- Innovative methods and instrumentation are currently under development to estimate parameters that control waterflow in fractured aquifers and to experimentally measure micropore and macropore flows in soil.
- Statistical and geostatistical techniques are being developed or adapted to estimate and describe the spatial variability of key soil, geographic, and geologic properties that influence the leaching of nitrate into groundwater. The potential for incorporating developments in remote sensing technology to improve these estimates is also being explored.
- Consideration will be given to modifying soil and crop management practices to exploit the fact that high-yielding corn hybrids—unlike older, lower yielding hybrids—frequently remain green and take up N actively from the soil during the grain-fill period.
- Microcomputers are available, sensors are being developed, affordable guidance systems are coming on the market, and knowledge of optimum plant growth requirements is being gained. Through utilization of these advances in scientific knowledge and technology, systems are being marketed that allow precision application of fertilizers. Further advances will allow producers to be able to sense changing soil conditions (for example, bulk density, water content, organic matter content, nutrient status) across a field and adjust the farm operation to create as near optimum conditions as possible for plant growth and N-use efficiency on each acre.

References

CAST. 1985. Agriculture and groundwater quality. Council for Agricultural Science and Technology Report 103, 62 pp.

Follett, R.F., S.C. Gupta, and P.G. Hunt. 1987. Conservation practices: Relation to the management of plant nutrients for crop production. In R.F. Follett, J.W.B. Stewart, and C.V. Cole, eds., Soil Fertility and Organic Matter or Critical Components of Production System, pp. 19-51. Soil Science Society of America Special Publication 19.

Keeney, D. 1986. Sources of nitrate to groundwater. CRC, Critical Reviews in Environmental Control 16:257-304.

Madison, R.J., and J.O. Brunett. 1985. Overview of the occurrence of nitrate in ground water of the United States. In U.S. Geological Survey Water-Supply Paper 2275, pp. 93-105.

Reeder, J.D., and Burns Sabey. 1987. Nitrogen. In R. Dean Williams and Gerald E. Schuman, eds., Reclaiming Mine Soils and Overburden in the Western United States: Analytical Parameters and Procedures, pp. 155-184. Soil Conservation Society of America.

U.S. Department of Agriculture. [In press.] Agricultural Statistics 1987. U.S. Department of Agriculture.

U.S. Department of Agriculture, Agricultural Research Service. 1985. Agricultural Research Service Program Plan: 6-year Implementation Plan, 1986-1992, 38 pp. U.S. Department of Agriculture, Agricultural Research Service.

U.S. Department of Agriculture, Soil Conservation Service. 1987. 1987 Soil and water conservation research and education progress and needs, 126 pp. U.S. Department of Agriculture, Soil Conservation Service.

U.S. Environmental Protection Agency. 1976. Quality criteria for water. U.S. Environmental Protection Agency, Washington, DC.

U.S. Environmental Protection Agency. 1982. Maximum contaminant levels (subpart B of part 141 national interim primary drinking-water regulations): U.S. Code of Federal Regulations, Title 40, Parts 100 to 149 (revised), pp. 315-318.

Viets, F.G., Jr., and R.H. Hageman. 1971. Factors affecting the accumulation of nitrate in soil, water, and plants. U.S. Department of Agriculture, Agriculture Handbook 413, 63 pp.

☆U.S. GOVERNMENT PRINTING OFFICE:1988-201-020:60542/ARS